Discrepancy in the cross section minimum of elastic nucleon-deuteron scattering

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Δ-isobar excitation in the nuclear medium yields an effective three-nucleon force. A coupled-channel formulation of nucleon-deuteron scattering with Δ-isobar excitation developed previously is used. The three-particle scattering equations are solved by a separable expansion of the two-baryon transition matrix below the inelastic threshold of pion production. The effect of Δ-isobar excitation on the spin-averaged differential cross section is studied. The discrepancy between theory and experiment in the diffraction minimum is reduced. [S0556-2813(98)06510-8]

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Virtual Δ-isobar excitation yields an effective three-nucleon force in the nuclear medium. A Δ-isobar gets created when a nucleon (N), through two-nucleon scattering in the medium, is internally excited. Theoretically, the process is described by a coupled-channel two-baryon interaction. Such a coupled-channel interaction is applied in Ref. [1] to the three-nucleon bound state. Reference [2] extends its application to elastic nucleon-deuteron scattering. In addition to [2], this paper concentrates on the description of the spin-averaged differential cross section around the diffraction minimum. It describes experimental data for elastic proton-deuteron scattering up to 135 MeV proton lab energy. Past calculations [3–6], based on traditional two-nucleon potentials, failed in the region of the diffraction minimum. This failure is often called Sagara discrepancy. The paper explores the effect of the particular three-nucleon force mediated by the Δ-isobar on the differential cross section.

The calculational scheme is taken over from Refs. [2] and [7]. The Hilbert space of the calculation has a purely nucleonic sector and a sector in which a nucleon is turned into a Δ-isobar. The Δ-isobar is considered a stable baryon with mass 1232 MeV and with spin and isospin $\frac{3}{2}$; that treatment of the Δ-isobar is appropriate below the pion-production threshold; the considered scattering energies stay well below. The two-baryon potential is the parametrization A2 of Ref. [7]; its purely nucleonic reference potential is the Paris potential [8]; comparison of results with both potentials allows the isolating of the Δ-isobar effect on observables. The three-particle AGS scattering equations [9] with channel coupling are solved by a separable expansion of the two-baryon transition matrix. That separable expansion is judged in Ref. [7] to remain valid for the considered scattering energies. In addition, Fig. 1 suggests that even at 135 MeV nucleon lab energy the inclusion of two-baryon partial waves up to two-baryon total angular momentum $I=3$, as done in this paper, is sufficient for a dynamically reliable description of elastic nucleon-deuteron scattering. Furthermore, since the effect of the two-baryon interaction in partial waves of total angular momentum $I=3$ is, according to Fig. 1, small indeed, the neglect of channel coupling in the only isospin triplet $I=3$ partial wave ${}^3F_3$ is also well justified. The claimed convergence with respect to the two-baryon total angular momentum I was also checked in Ref. [5]. Reference [5] sees a small effect at 135 MeV of comparable order of magnitude as shown in Fig. 1 when partial waves with total angular momentum $I=4$ are included; we are unable to push our own calculation to such a technical perfection at present and therefore have to rely on the result of Fig. 1. The calculation takes three-baryon channels up to three-baryon total angular momentum $\frac{31}{2}$ into account. The calculation is done without Coulomb interaction. However, the experimental data to be described refer to proton-deuteron scattering. The Coulomb interaction is known to yield sizable corrections for the dif-

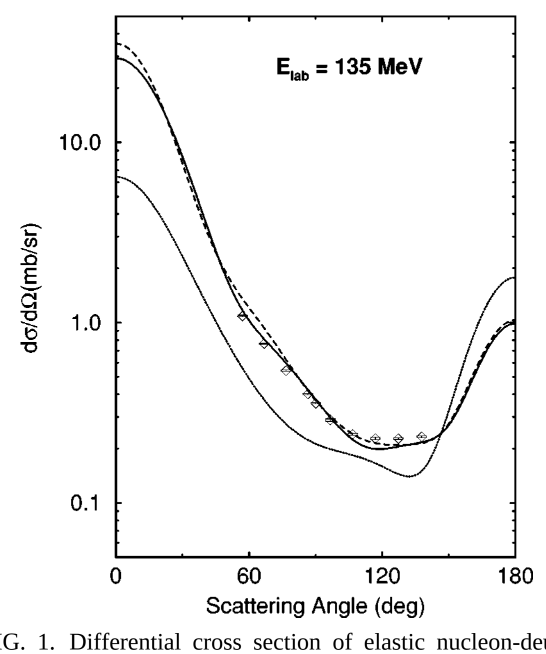

FIG. 1. Differential cross section of elastic nucleon-deuteron scattering at 135 MeV nucleon lab energy. The calculated cross section is based on the two-baryon potential A2 of Ref. [1]. The importance of a nonzero parametrization in the partial waves of total two-baryon angular momentum I is studied. In the result, indicated by the full (dashed, dotted) curve, the interaction is nonzero in all partial waves up to $I=3$ ($I=2$, $I=1$). A calculation up to $I=3$ appears well converged, the effect arising from the $I=3$ partial waves appears small. The experimental data are taken from Ref. [5].

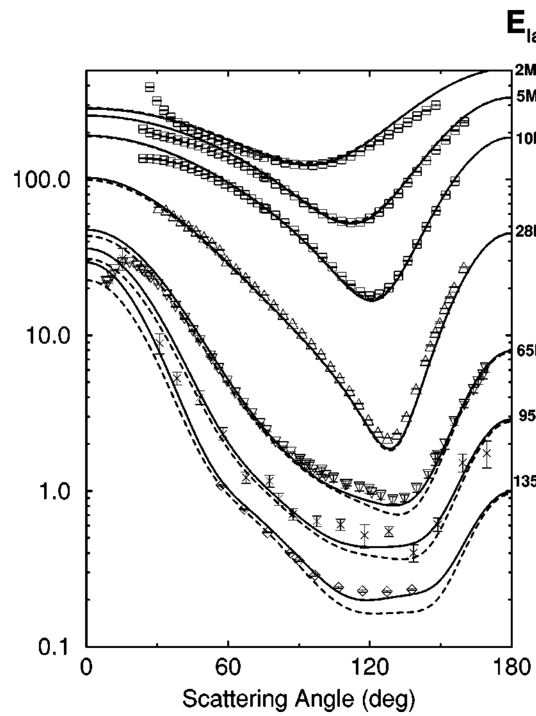

FIG. 2. Differential cross sections of elastic nucleon-deuteron scattering as function of the c.m. scattering angle for 2 MeV, 5 MeV, 10 MeV, 28 MeV, 65 MeV, 95 MeV, and 135 MeV nucleon lab energy. The differential cross sections derived from the coupled-channel potential with Δ-isobar excitation (solid curves) are compared with results based on the purely nucleonic reference potential (dashed curves). The experimental data refer to proton-deuteron scattering; they are taken at 2 MeV, 5 MeV, and 10 MeV from Ref. [3], at 28 MeV from Ref. [14], at 65 MeV from Ref. [15], at 95 MeV from Ref. [16], and at 135 MeV from Ref. [5].

ferential cross section at all scattering angles below 5 MeV proton lab energy and in forward direction at all energies; in fact, Ref. [10] sees Coulomb effects up to about 70° scattering angles at 65 MeV proton lab energy and up to about 50° at 135 MeV. In contrast, this paper discusses the differential cross section in the region of the diffraction minimum; that region appears not to be influenced appreciably by the Coulomb interaction above 5 MeV proton lab energy.

We present our results for the differential cross section of nucleon-deuteron scattering at seven energies in Fig. 2. Up to 10 MeV nucleon lab energy the effect of the Δ-isobar is invisible on the log-plot. At higher energies it appears beneficial for the theoretical prediction. It decreases the Sagara discrepancy. The same effect was already seen in Ref. [11]. The experimental data for 95 MeV carry large error bars and do not allow firm conclusions. In Figs. 3–5 we try to understand the role which the Δ-isobar plays for the results in more detail. We define the discrepancy

$$\Delta\sigma(\theta)\equiv\frac{\frac{d\sigma^{\mathrm{calc}}}{d\Omega}(\theta)-\frac{d\sigma^{\mathrm{exp}}}{d\Omega}(\theta)}{\frac{d\sigma^{\mathrm{exp}}}{d\Omega}(\theta)}\times 100 \tag{1}$$

between theoretical prediction and experimental data as in Ref. [3]. Figure 3(a) shows that discrepancy $\Delta\sigma(\theta_{\mathrm{min}})$ at the minimum of the cross section for all considered energies.

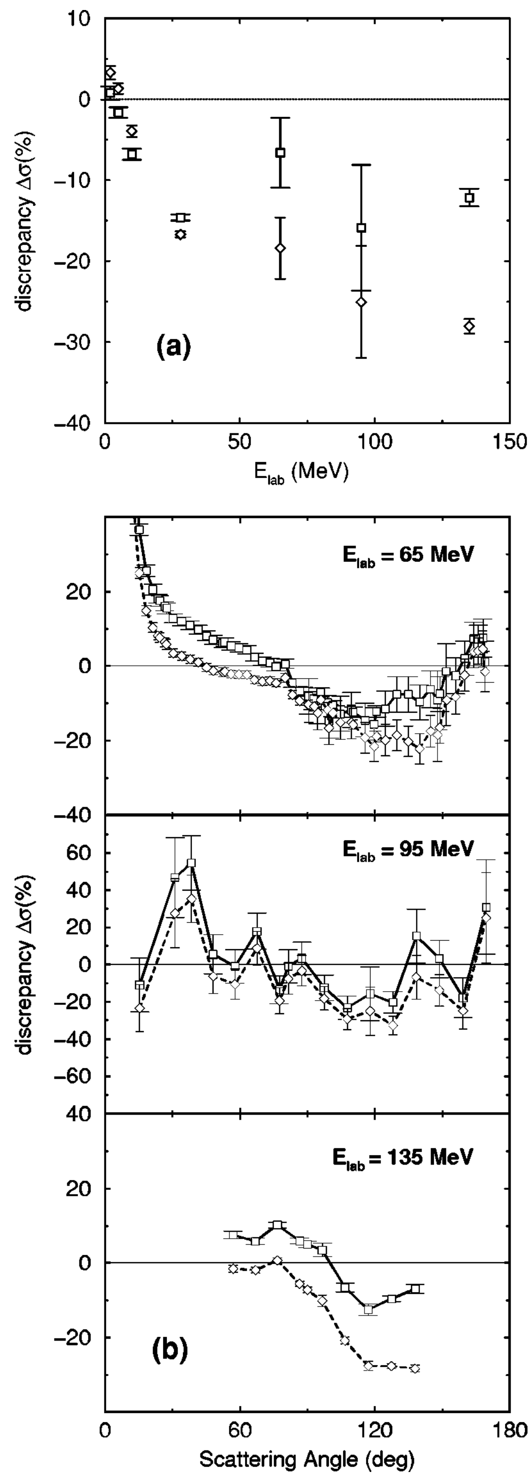

FIG. 3. Discrepancy $\Delta\sigma$ between experimental data and theoretical prediction for the nucleon-deuteron differential cross section according to Eq. (1). Results with (□) and without (◇) Δ-isobar excitation are compared. The error bars reflect uncertainties in the experimental data only; no attempt is made to estimate the systematic uncertainties of the calculation. (a) The discrepancy at the experimental minimum of the differential cross section as a function of energy. The scattering angles θ_{min} in the experimental minimum are 94.6°, 112.8°, 120.7°, 128.0°, 131.3°, 116.7°, and 120.0° for 2 MeV, 5 MeV, 10 MeV, 28 MeV, 65 MeV, 95 MeV, and 135 MeV nucleon lab energy, respectively. (b) The discrepancy as a function of scattering angle for 65 MeV, 95 MeV, and 135 MeV nucleon lab energies, respectively.

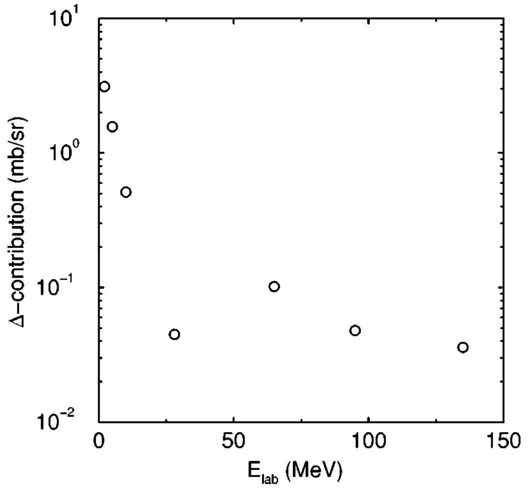

FIG. 4. Δ-contribution $|(d\sigma^{\rm calc}/d\Omega(\theta_{\rm min})|_{N\Delta}-d\sigma^{\rm calc}/d\Omega(\theta_{\rm min})|_{N})|$ to the cross section at the experimental minimum. As can also be derived from Fig. 3(a), that difference is negative for the three lowest energies 2 MeV, 5 MeV, and 10 MeV.

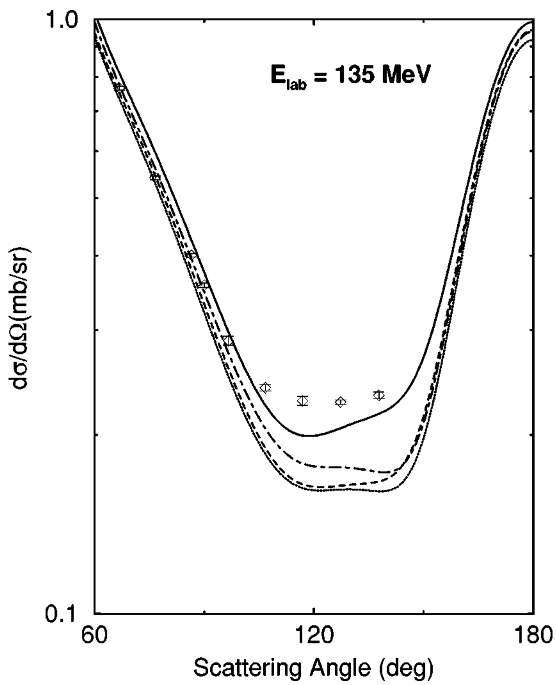

FIG. 5. Differential cross section of elastic nucleon-deuteron scattering at 135 MeV nucleon lab energy as function of the c.m. scattering angle. The effect of Δ-isobar excitation is studied in detail. The full results with and without Δ-isobar excitation are given by the solid and dashed curves. In the results, indicated by the dotted and the dashed-dotted curves, Δ-isobar excitation is allowed by coupling to the $^1S_0$ and to the $^1S_0{-}^3P_I$ NN partial waves. The displayed results prove that the full Δ-isobar effect is a complicated interference phenomenon. The most important NΔ partial waves are those coupled to the ^3P_I and $^1D_2$ NN partial waves. The experimental data are taken from Ref. [5].

The experimental minimum position $\theta_{\rm min}$, the cross section value, and its error are determined by fitting the available data points. The Δ-isobar effect in $\Delta\sigma(\theta_{\rm min})$ increases with energy. We observe the crossing of zero as in Ref. [3]; with Δ-isobar excitation the crossing is shifted to lower energies. With Δ-isobar excitation the calculated differential cross section in the diffraction minimum remains always lower than the experimental one, except at 2 MeV. At 10 MeV the Δ-isobar even worsens the agreement in the diffraction minimum, though the discrepancy remains comparatively small. Figure 3(b) shows the discrepancy for all scattering angles at three energies, i.e., at 65 MeV, 95 MeV, and 135 MeV. The discrepancy has different characteristics for forward and for backward scattering angles. The Δ-isobar improves the agreement between theoretical prediction and experimental data for backward angles, i.e., for $\theta > 90°$; there our calculation is quite reliable and there the discussed diffraction minimum is located. However, the Δ-isobar worsens the agreement for forward angles, i.e., for $\theta < 90°$; but this angular regime is still sensitive to Coulomb corrections; there our calculation becomes poorer the smaller the scattering angle gets. Figure 4 also proves that the effect of the Δ-isobar on the differential cross section in the diffraction minimum, i.e., $d\sigma^{\rm calc}/d\Omega(\theta_{\rm min})|_{N+\Delta}-d\sigma^{\rm calc}/d\Omega(\theta_{\rm min})|_{N}$, the subscript $N+\Delta$ (N) indicating the full calculation with all considered $N\Delta$ partial waves (the calculation with nucleons only in all partial waves), indeed decreases with energy. Since, however, the differential cross section as a whole becomes rapidly smaller with increasing energy, the Δ-isobar effect gets more visible at higher energies and there especially in the diffraction minimum. Figure 5 tries to pin down where the effect of the Δ-isobar comes from. It proves that it is a complicated interference phenomenon; the $N\Delta$ partial waves coupled to the purely nucleonic ^3P_I and $^1D_2$ waves are most important, yielding 75% of the Δ contribution $d\sigma^{\rm calc}/d\Omega(\theta_{\rm min})|_{N+\Delta}-d\sigma^{\rm calc}/d\Omega(\theta_{\rm min})|_{N}$ at 135 MeV.

We see a beneficial Δ-isobar effect in the diffraction minimum of the spin-averaged differential cross section for elastic nucleon-deuteron scattering at higher energies; the Δ-isobar helps to remove the long-standing Sagara discrepancy there. However, with regret, we also observe that the Δ-isobar effect even increases discrepancies at other scattering angles; the effect is simply not as visible there on the traditional log-plot. The found results, in their positive and negative implications, still have to be taken with some caution; it has to be checked that they are not accidental to the particular form of our dynamic model. The Δ-isobar effect may possibly be changed by corrections omitted until now, e.g., by Coulomb corrections for proton-deuteron scattering as emphasized in Refs. [10, 12] and by the influence of higher partial waves. Relativistic corrections are unlikely to be effective [4] at the energies considered. Clearly, the observations of this paper deserve further study. In this context, we are pleased to see that a complementary calculation [13] on the same problem, using a traditional irreducible and not an effective three-nucleon force, arrives at similar conclusions as this paper does.

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